

# **A Study of Internal Waves and Turbulence Above Irregular, Sloping Bathymetry: A Contribution to the Littoral Internal Wave Initiative (LIWI)**

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## **LONG-TERM GOALS**

The long-range goal of our studies is to understand the processes that cause mixing in the ocean. Of particular interest is the turbulence caused by internal wave breaking. Our recent work has revealed strong relationships between finescale shear levels and the intensity of turbulent mixing, and marked spatial variability in the intensity and characteristics of the internal wave field. These observations suggest a strong correlation between enhanced fine- and microstructure and proximity to rough bathymetric structures. We seek to develop sufficient understanding of internal waves near such bathymetry as to produce models that can predict the magnitude and variability of turbulent mixing resulting from internal wave breaking.

## **OBJECTIVES**

We will be conducting a field program in May of 1998 to quantify finescale internal wave characteristics above a region of irregular, sloping bathymetry. Our chief focus will be on two basic mechanisms for modifying the internal wave field in the littoral zone: internal wave generation at, and wave reflection from, the bottom. Both can result in enhanced internal wave shear and strain, and in turn, increased occurrence of shear and/or advective instability supporting turbulence and mixing.

Internal waves are generated when currents impinge on bathymetric features and force vertical motion at the bottom. In particular, we are interested in the response to alongshore currents, associated with the surface tide and sub-inertial currents, flowing over small-scale (~1 km horizontal wavelength) features on the continental slope. Theoretical treatments suggest these latter flows can give rise to internal waves with small horizontal (~1 km) and vertical (~100 m) wavelengths in the littoral zone (Bell, 1975). Such waves contribute significantly to vertical shear, and consequently have a more direct influence on turbulent dissipation and mixing than waves with large vertical scales (Polzin *et al.*, 1995).

As is now well known, internal waves undergoing reflection from a sloping bottom can have their vertical and horizontal wavelengths greatly modified (Phillips, 1977). In particular, internal waves propagating towards a planar slope with wave-characteristics nearly paralleling the bottom experience a significant decrease in horizontal and vertical scale. The decrease in spatial scales again implies increased shear, strain and mixing.

Our objectives in this current grant are two fold. First, we will be testing and refining models of wave generation/reflection. Secondly, we will develop and test dynamical models which predict the spatial and temporal evolution of an enhanced finescale internal wavefield as it propagates away from the bottom boundary. Such dynamical models will result in a prediction of the rate at which internal wave energy dissipates and results in turbulent mixing.

## **APPROACH**

Our approach to the field program is to utilize a combination of vertically profiling instrumentation. The first instrument is the freely falling High Resolution Profiler (Schmitt *et al.*, 1988) which obtains samples of the ocean's temperature, salinity, and horizontal velocity field and the associated dissipation rates of turbulent kinetic energy and temperature variance. The second instrument is a moored profiling instrument system (termed the Moored Velocity Profiler, MVP) which is able to sample oceanic finescale velocity, temperature and salinity variability.

The experimental site is characterized by well defined, small horizontal scale (2.5–3 km horizontal wavelength) ridges oriented onshore-offshore and superimposed on a large-scale planar slope. Three MVP's will be deployed as a coherent array with an approximate spacing of 500 m. The array will be located in about 1500 m water depth on the continental slope just north of Cape Hatteras (37° 10'N, 74° 25'W). The HRP will be used to repeatedly sample a grid of stations in water depths of 500–2000m about the MVP array. In combination, the HRP and MVP data will allow us to characterize the amplitude, direction of propagation, and frequency of the finescale internal wavefield.

In differentiating between possible sources of energy for the finescale wavefield, whether it be by wave generation or wave reflection, it is important to ascertain the direction of

wave propagation and wave frequencies. We have previously attempted to obtain estimates of wave propagation direction from isolated vertical profiles and linear kinematics (e.g. Polzin *et al.* 1995). If the wavefield is composed of more than a single wave, though, interpretation of such (e.g. Polzin et al 1995) diagnostics becomes uncertain.

The difficulties inherent in the diagnostics discussed above can be overcome if direct estimates of either frequency or horizontal wavenumber are obtained in addition to vertical wavenumber. The coherent array of MVP instruments will return estimates of dominant horizontal wavenumbers for each vertical wavenumber from coherence estimates, analogous to Eriksen's (1996) study. Inclusion of HRP profile data at other spatial separations will facilitate construction of horizontal wavenumber spectra.

Our research effort benefits from the technical support of several people here at WHOI. Ellyn Montgomery maintains the HRP sensors and control processor and its associated data acquisition and reduction systems. The instruments mechanical systems are maintained by David Wellwood. Maggie Cook and Gwyneth Packard assist the PI's with reduction and analysis of the acquired data. The Moored Velocity Profiler technical activities are being supported by folks in Institution's Advanced Engineering Laboratory.

## WORK COMPLETED

As we are still in the preparatory phase for the field program, none of our program tasks have been completed. In advance of the LIWI field work, we have begun collecting existing ancillary data (e.g. digitized bathymetry products, historical current meter and CTD data) from the experiment site. In parallel, we are working to develop models of internal wave generation, interaction, and dissipation. With the historical data and theory, we are working to optimize the sampling strategy.

## RESULTS

To date, most of our effort has been spent developing a method which permits a theoretical estimate of the vertical profile of turbulent dissipation associated with internal wave breaking. An equation has been derived for the evolution of the vertical wavenumber energy spectrum:

$$\frac{\partial E}{\partial t} + C_{gz} \frac{\partial E}{\partial z} + \frac{\partial F}{\partial m} = 0 \quad (1)$$

In (1), the time rate of change of energy density is balanced by the divergence of the vertical energy flux  $(C_{gz}E)$  and the divergence of spectral energy fluxes through vertical wavenumber space ( $F$ ). The vertical wavenumber energy density ( $E$ ) is a function of time, vertical wavenumber and height from the bottom boundary. The problem is closed by invoking an analytical representation of energy transfers to higher wavenumber associated

with internal wave/wave interactions and WKB (buoyancy) scaling of the vertical wavenumber in order to express  $F$  in terms of  $E$  and  $N$ . This results in a non-linear partial differential equation for the vertical wavenumber spectrum:

$$\frac{\mathcal{I}E}{\mathcal{I}t} + C_{gz} \frac{\mathcal{I}E}{\mathcal{I}z} + w \frac{\mathcal{I}}{\mathcal{I}m} \left\{ E \frac{\mathcal{I}N}{\mathcal{I}z} N^{-1} + A m N^{-2} E \int_0^m m'^2 E dm' \right\} \quad (2)$$

In (2),  $A$  is a constant ( $A \sim 0.1$ ). The rate of dissipation of turbulent kinetic energy is equated with the up wavenumber energy fluxes ( $F$ ) at high vertical wavenumber, resulting in an estimate of dissipation versus depth. Approximate analytic solutions to this equation have been found in the steady limit ( $\mathcal{I}E/\mathcal{I}t$ ):

$$E(m, z) = \left\{ \frac{b}{1 + 2AbN_0^{-4} m_0^4 \int_0^z N^2(z') dz'} \right\} \frac{m_0^2 N^2}{m^2 N_0^4} \left\{ 1 - \frac{1}{2} \frac{m_0^2 N^2}{m^2 N_0^2} \right\} \quad (3)$$

In (3),  $N_0$  is the buoyancy frequency at the bottom boundary. The dependence of the energy spectrum on vertical wavenumber is characterized by an amplitude  $b$ , a peak at  $m_0$ , and a high wavenumber decay of  $m^{-2}$ . These solutions allow us to conclude that:

- For a given rms velocity in the internal wavefield, significant dissipation are possible if that energy is generated at small vertical scales. Decreasing the peak vertical wavelength by a factor of two results in a factor of four increase in dissipation at the bottom boundary. Because high dissipation rates are associated with small vertical scale motions, the amplitude of a small scale wavefield decreases quickly with increasing height from the bottom boundary. As a corollary, wave generation into large vertical scales does not contribute significantly to the enhancement of turbulent dissipation in the near bottom region.
- The vertical decay of internal wave energy associated with dissipation is extremely sensitive to the energy in the wavefield. Increasing the rms velocity by a factor of two results in a 16 fold increase in turbulent dissipation at the bottom boundary.
- The vertical decay of internal wave energy associated with dissipation is independent of wave frequency for wave frequency  $f \ll w \ll N$ .
- Changes in vertical wavenumber associated with changes in  $N^2$  (WKB scaling) result in surprisingly little change in the vertical profile of turbulent dissipation unless the peak wavelength is large and the amplitude is small.

## **IMPACTS/APPLICATIONS**

The approach we have taken in developing a dynamical model to describe the energetics of the small scale internal wavefield is novel. While highly idealized in its present form, we expect that appropriate modifications can be made to provide robust estimates of the spatial and temporal evolution of the internal wavefield and turbulent dissipation in continental slope regions. The field program described above will help ground truth the model.

## **TRANSITIONS**

A manuscript describing the dynamical model results outlined above is in preparation. The results have been presented in seminars at the University of Washington and the University of Victoria.

## **RELATED PROJECTS**

We will be using three Moored Velocity Profilers in the field experiment. Alterations to the pre-existing Moored Profiler, which carried only a CTD, are being funded by ONR (grant to J. Toole and R. Schmitt). As well, refurbishing of the prototype MVP and construction of two new MVPs is being funded under a companion DURIP grant (J. Toole and D. Frye).

Eric Kunze (UW, XCP and XCTD deployment) will be participating in the field program. Finally, the insight gained as part of this grant will have a direct impact on the interpretation of HRP and tracer data acquired during the Brazil Basin Experiment (NSF grants to J. Ledwell, J. Toole and R. Schmitt).

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